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QSO METAL-LINE ABSORBERS: THE KEY TO LARGE-SCALE STRUCTURE?

A.P.S. CROTTS,[1] A.L. MELOTT[2,3], and D.G. YORK[3]
University of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637, USA

and

J.N. FRY
Department of Physics, University of Florida, Gainesville, FL 32611 USA

Received ______________

A study of the spatial autocorrelation of heavy-element-containing absorption systems in QSOs has shown strong clustering. Based on this correlation, it is proposed that more data may facilitate study of large-scale structure at larger scales and earlier epochs than previously possible. It may be possible to measure the slope of the primordial power spectrum, and set a new lower bound on the mass density of the universe in nonrelativistic species, including the unknown dark matter, whether or not it is baryonic.

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1. *Department of Physics*
2. *Enrico Fermi Postdoctoral Fellow*
3. *Department of Astronomy and Astrophysics and Enrico Fermi Institute*

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The formation of structure on large scales in the Universe is most commonly assumed to have proceeded from the gravitational growth of a power law spectrum of density perturbations

$$<|\tilde{\delta}(\mathbf{k})|^2> \sim k^n \tag{1}$$

where $\mathbf{k}$ is a wavevector, $k \equiv |\mathbf{k}|$, and the $\tilde{\delta}(\mathbf{k})$ are the Fourier components of the mass density [1]. The presently observed value of n, using galaxies as mass tracers is about -1 [2], but such a value can arise from nonlinear evolution of a variety of initial conditions [3]. Furthermore, since metric fluctuations

$$\delta\phi \sim R^{(1-n)/2} \tag{2}$$

for a length scale R, the observed value would lead to large-scale divergence. There is obvious aesthetic appeal to $n=1$, but larger values with a cutoff at large k arise in some scenarios [4]. It is of great interest both for processes in the very early Universe and for understanding galaxy formation to know the primordial index n, or any deviation from power law behavior.

In order to infer the primordial power spectrum, it is necessary to observe in the linear regime, where growth is still self-similar. This can be accomplished by observing the matter distribution at large scales and earlier times. One of us [5] has calculated the autocorrelation of QSO absorption line systems identified by spectral lines of elements other than hydrogen. Such absorption lines typically have velocity widths of 50 to 1000 $km\ s^{-1}$. Many are thought to arise in intergalactic space.

The observations were taken from a recent catalog of QSO absorption spectra [6]. The original 653 systems in 193 QSOs were subjected to judgment criteria, in which redundant, conflicting, weakly justified or hydrogen-line-only redshifts were removed. Also removed were redshifts due to broad absorption line features (those with widths $\geq$2000 $km\ s^{-1}$, probably due to matter directly associated with QSOs [7]), absorption local to the Galaxy and vicinity, and multiple incidences of absorption redshifts in lensed QSO systems, leaving 350 systems in 151 QSO spectra.

From this sample, a set of Monte Carlo catalogs were constructed by the method outlined in [5]. These catalogs consist of simulated redshifts distributed in the same lines of sight as toward the real QSOs, but arranged in a way consistent with the selection effects found in the real catalog. The consistency of the selection biases in the real and Monte Carlo catalogs was checked by use of the Kolmogorov-Smirnov test for identical distributions.

The density of pairings of absorption systems, as a function of radial separation between the two systems in each pair, was compared for the real and Monte Carlo catalogs, allowing one to compute the two-point correlation function, ξ, as described in [1]. Figure 1 shows ξ as a function of a comoving coordinate separation r, for absorption systems of all redshifts, assuming $q_0=1/2$ and $h \equiv H_0/100\ km\ s^{-1}\ Mpc^{-1}$. The first two 30 h^{-1} Mpc bins summed together produce a marginally significant positive correlation. Most of the power in the first bin, however, is due to very strong correlation for 300 h^{-1} $kpc \leq r \leq 2$ h^{-1} Mpc.

The correlation found could be much stronger than that of galaxies, and comparable to that of rich clusters of galaxies [8,9]. Increased amplitude can be explained as a statistical effect if both rich clusters and the absorbers studied here are high peaks of the original distribution [10,11].

We wish to point out that a variety of cosmological tests may be performed using this method, with an improved data set. In principle, by Fourier transforming the two-point correlation in Fig. 1 we can show the power spectrum. However, at present the power spectrum only shows significant signal corresponding to the correlation seen in the first two 30 h^{-1} Mpc bins.

Statistical arguments [10,11] have been presented to show that when we confine our attention to density peaks in a distribution, the resulting correlations are linearly amplified copies of the correlations of the underlying distribution at least so long as we look on scales larger than those on which the amplified signal is nonlinear. Numerical work [12] indicates that this effect is real, and that the restriction to large scales may not be necessary. An approach based on renormalization, however, suggests that the amplification may not be linear [13]. Part of the rationale for our proposal depends on the assumption that the amplification is linear. Numerical work [12] supports the contention that the amplification is linear if gravity is the process leading to large scale structure formation in the Universe.

Let us estimate the increase in the existing data set necessary to give a meaningful signal at large radii. From observations of galaxies, the two-point correlation is

$$\xi(r)=\left(\frac{r_0}{r}\right)^{\gamma} \tag{3}$$

with $\gamma\approx1.8$ and $r_0\approx5\ h^{-1}\ Mpc$, [14,15]. The value of r_0 for rich clusters is much larger [8,9] but γ is about the same. Recent results discussed here [5] indicate that r_0 could be much larger for the absorbers.

In the usual normalization

$$\tilde{\delta}(\mathbf{k})=N^{-1}\overline{\eta}\int d^3r\ \delta(\mathbf{r})\ e^{i\mathbf{k}\cdot\mathbf{r}}, \tag{4}$$

where N is the number of points, and $\overline{\eta}$ is the mean density of points. The power spectrum of the density distribution is

$$P(k)\equiv\langle|\tilde{\delta}(\mathbf{k})|^2\rangle=\frac{1}{N}\left[1+\overline{\eta}\int d^3r\ \xi(r)\ j_0(kr)\right], \tag{5}$$

for $k\neq0$ and where j_0 is a spherical Bessel function [1]. Discreteness produces the first term, a "shot noise" present even when $\xi=0$, while the second arises from physical clustering. The number of excess pairs due to clustering can be written [1]

$$N_c(k)\equiv\overline{\eta}\int d^3r\ \xi(r)\ j_0(kr)=\frac{2\pi^2(\gamma-1)}{\Gamma(\gamma)\ \sin[(\gamma-1)\frac{\pi}{2}]}\overline{\eta}k^{-3}(kr_0)^{\gamma} \tag{6}$$

for $\xi=(r/r_0)^{-\gamma}$. For the observed galaxy distribution out to $r=10\ h^{-1}\ Mpc$ (and for Abell galaxy clusters out to $r=100\ h^{-1}\ Mpc$), $\gamma\approx1.8$ and $N_c(k)=(0.82)2\pi^2\overline{\eta}k^{-3}(kr_0)^{\gamma}$ (one often sees $N_c(0)$ written as $4\pi\overline{\eta}J_3$).

Ideally, the expected mean square variation of power can be computed from $\langle(\Delta P)^2\rangle=\langle|\tilde{\delta}(\mathbf{k})|^4\rangle-\langle|\tilde{\delta}(\mathbf{k})|^2\rangle^2$ to be

$$\frac{\langle(\Delta P)^2\rangle}{P^2}=1+\frac{1}{N}\frac{[1+2N_c(0)+4N_c(k)+N_c(2k)]}{[1+N_c(k)]^2} \tag{7}$$

ignoring contributions from the three- and four-point correlation functions. The term proportional to $1/N$ is again the result of discreteness and is insignificant in both strong and weak clustering regimes if N is large. Contributions to the other term arise from both discreteness and physical clustering. Expected errors in estimates of $P(k)$ will be (7) divided by the number of independent volumes sampled, $N_k=k^3V/(2\pi)^3$.

We expect to work in the regime of weak clustering, $N_c\lesssim1$, but with $N>100$. The uncertainty in P will be mainly from the discreteness contribution, $\Delta P=P/\sqrt{N_k}=1/N\sqrt{N_k}$. The ratio of ΔP to P_{cl} determines whether or not we can detect P_{cl}. We need $\Delta P/P_{cl}=1/S\lesssim1/3$ ($S\equiv$"signal-to-noise" ratio) to have significant detection. Thus, we need

$$\frac{\Delta P}{P_{cl}}=\frac{N_k^{-1/2}}{N_c(k)}=(1.2)(\frac{2}{\pi})^{1/2}\frac{(k^3V)^{1/2}}{(kr_0)^{\gamma}}\frac{1}{N}\leq\frac{1}{S} \tag{8}$$

or ($\gamma=1.8$)

$$k^{-1}\equiv\frac{r}{2\pi}\leq(0.52)\left(\frac{\pi}{2}\right)^{5/3}S^{-10/3}\ V^{-5/3}\ r_0^{6}\ N^{10/3} \tag{9}$$

This says that the distance to which one can detect clustering grows rapidly with the number of objects sampled, assuming the number of objects sampled does not exceed the total number of objects available in V, so $N/V \leq \bar{\eta}$. One expects to be able to see clustering to a scale

$$r \lesssim 6.9\ S^{-10/3}\ N^{10/3}\ V^{-5/3}\ r_0^{6}. \qquad (10)$$

With $S=3$, $V \approx (1000\ h^{-1}\ Mpc)^3$, and $r_0 \approx 30\ h^{-1}\ Mpc$ (the value for Abell clusters), certainly we can see to several hundred Mpc with $N \gtrsim 10^3$.

This calculation assumes ideal conditions; estimates need to be performed via Monte Carlo techniques to fold in all of the biases and selections present in real observations. We have seen [5] that many systematic effects can be eliminated even for data taken under various conditions. It is preferable, however, to be able to remove these effects a priori by performing a uniform set of observations.

To achieve $N \approx 10^3$ and $V \approx (1000\ h^{-1}\ Mpc)^3$, we suggest a complete, magnitude-limited survey of QSO absorption line systems over an area about 0.25 sterradian in the sky. With a QSO surface density of order 1 per square degree at $m_V = 18.^m5$, we note that this implies an effort three times greater than the sum of all previous such observations. The subsequent improvement in S will come primarily from an increase in density of sampling points of order $4\pi/0.25$. This will extend our knowledge of the structure of the Universe to large scales at early times. It would be of great theoretical importance to find the turnover to positive n. If $r_0 = 5\ h^{-1}\ Mpc$, we would need a larger survey. Absorption systems containing only hydrogen lines could be used instead of metal-line systems (approximately 30 times more would be seen in this survey). No clustering of hydrogen-only systems has yet been demonstrated, but the proposed technique would be more sensitive to spatial correlations than those used previously [5].

It also will make possible a cosmological test of Ω_T, the total mass density of the Universe. Density perturbations always grow in a matter-dominated Universe with $\Omega \geq 1$; if $\Omega < 1$, the value of Ω converges on 1 as we look back to increasingly earlier times. In a low-density Universe, perturbations which are still linear grow until a redshift $(1+z) \sim \Omega_0^{-1}$, at which time they begin to freeze out; their growth is greatly suppressed.

If our absorbers are grouped into redshift bins, and by examination of their clustering properties we can demonstrate growth of clustering on scales where the density contrast is linear, then we may conclude that

$$\Omega_0 > (1+z_G)^{-1} \qquad (11)$$

where z_G is the redshift separating the bins and Ω_0 is the present value of Ω. The limit may be made more precise by comparison with integration of growth in low-density, matter-dominated universes [1]. We wish to stress that this limit will be independent of whether the matter density is baryonic or not. It is also independent of the matter's clustering. This interpretation is even stronger considering that clustering on scales above 10 Mpc is unlikely to have come about from pressure gradients [16].

It may also be possible to exclude models in which the universe has recently become (through particle decay) dominated by relativistic species [17,18]. The growth of density perturbations in matter is greatly suppressed in such models [19], and an observational demonstration of growth of density perturbations could strongly limit the physical parameters of these models.

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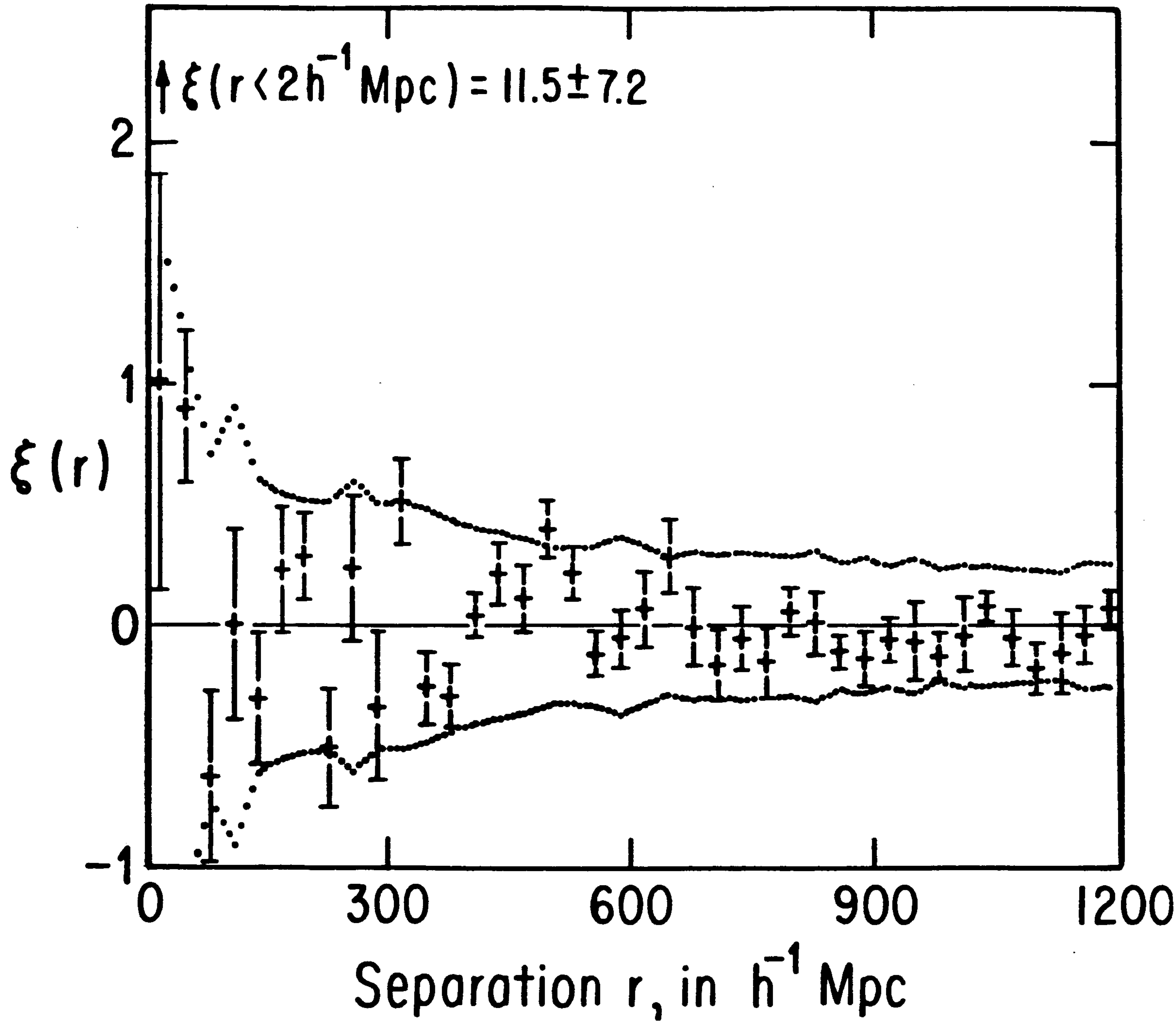
FIGURE 1: The two-point function of metal-line QSO absorbers of all redshifts > 0.01, as a function of a comoving separation r. The symbols $(+)$ denote the function binned at 30 h^{-1} *Mpc* intervals. The dotted curves correspond to the 95% confidence envelope for deviations from $\xi=0$. Error bars denote $\pm 1\sigma$ standard errors for the observed ξ. The value for $r<2$ h^{-1} *Mpc* is also shown.



$\uparrow \xi(r<2h^{-1}\,\mathrm{Mpc}) = 11.5 \pm 7.2$
2
1
0
−1
$\xi(r)$
0
300
600
900
1200
Separation r, in h^{-1} Mpc

FIGURE 1